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Energy savings with outdoor temperature-based smart ventilation control strategies in advanced California homes

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Disclaimer

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Abstract

We developed and simulated the energy performance of smart ventilation controls based on outdoor temperature in homes located in California climate regions, designed to comply with the 2016 Title 24, Part 6 California Energy Code prescriptive requirements. The smart controls shift ventilation rates in time, but ensure an annual occupant pollutant exposure equal to, or less than, what would be experienced in a home with a constant ventilation rate equal to the whole house target airflow in the ASHRAE Standard 62.2-2016. Annual simulations of previously developed prototype homes with validated ventilation models, were conducted via co-simulation of EnergyPlus with CONTAM. Controller performance varied substantially by climate zone, airtightness and house prototype. Smart controls were generally ineffective in Climate Zone 1 (Arcata) due to its lack of a cooling season and low diurnal temperature swings. The most successful smart controls used parameters pre-calculated using an optimization routine. In order to better inform state energy policy, we also determined savings weighted by the amount of new home construction in each climate. The best controls averaged about one-third of ventilation-related energy savings that increased to about 48-55% when weighted. Annual average savings were about 650-700 kWh/year for the best controllers. The vast majority of site energy savings were for heating end-uses (>90% of total savings). Whole house ventilation rates increased between 0 and 42%, with typical increases in the 15-20% range. The best-performing control strategies shifted ventilation rates seasonally and modulated flows within each season. Peak concentrations during low ventilation times were kept below an exposure level of 3, well below the maximum of 5 required to avoid acute exposure issues.

Keywords:

ventilation
smart buildings
smart ventilation
indoor air quality
residential energy efficiency

Abbreviations:

ACH50- Air changes per hour at 50 Pascal driving force
CEC- California Energy Commission
CZ- Climate Zone
FMI- Functional Mockup Interface
HVAC- Heating, Ventilation and Air-Conditioning
IAQ- Indoor Air Quality
Q_{fan}- Volumetric flow rate through dwelling unit fan
RE- Relative Exposure
RD- Relative Dose
SV- Smart ventilation

1 Introduction

Strategies for improving the energy performance of homes often begin with the tightening of building envelopes and reducing natural air exchange between indoor and outdoor environments, eventually necessitating mechanical ventilation. Mechanical ventilation is required in national residential energy standards (International Code Council 2018), in some state buildings codes (e.g. California's Title 24-2019: California Energy Commission, 2016), and voluntary programs. This study looks at solutions for providing ventilation adequate for ensuring acceptable indoor air quality (IAQ), while minimizing the energy penalty associated with conditioning and transporting ventilation air. Specifically, we look at "smart" ventilation (SV) strategies that involve modulation of ventilation fan states and speeds throughout the day or year in response to outdoor temperature, while maintaining acceptable indoor air quality (IAQ).

Following a thorough review of existing studies of ventilation control strategies (Guyot et al. 2017), we developed and analyzed options for temperature-based controls. We only studied homes with dedicated mechanical ventilation and did not explore natural ventilation strategies. We sought to isolate the variable of interest, namely the energy consequences of the ventilation control strategy, and to assess the "credit" that might be assigned in prescriptive codes in the State of California for various SV control strategies. For these reasons, we conducted our investigation via simulation of prototype homes previously used for the purpose of evaluation energy efficiency measures in advanced California homes (Nittler and Wilcox 2006). We simulated both air flow and energy consumption through simulation software platforms EnergyPlus and CONTAM (Dols, and Polidoro 2015) via a co-simulation process (Dols, Emmerich and Polidoro 2016). We paid particular attention to the interaction of ventilation systems and envelope air flow using a platform and envelope models that have been extensively validated in previous work (Emmerich 2001; Walker and Wilson 1998; Walker, Forest and Wilson 2005). Furthermore, we limited the scope of our study to strategies that do not require direct sensing of individual pollutants, and considered the homes to be well-mixed.

With this in mind, we pursued two objectives:

1. Provide guidance to the building community and the State of California on the most effective means of controlling ventilation fans in high-performing California homes while ensuring acceptable indoor air quality, as defined by ASHRAE Standard 62.2.

2. Determine the energy savings available with temperature-based ventilation control strategies to inform code development and educate stakeholders.

2 Background

In this study, we assess the energy performance of different control strategies that dynamically vary mechanical ventilation airflows, and we compare these smart controls against simple, constant flow scenarios that comply with ASHRAE Standard 62.2-2016. To ensure that resulting IAQ was the same in each case, we used the theory of equivalent ventilation (Sherman et al. 2011a; and Sherman et al. 2012). This theory assumes a generic pollutant is emitted at a constant rate, with no outdoor sources or removal processes other than air exchange. With these assumptions, the theory employs the concept of "relative exposure" (RE), both to assess IAQ performance, and to control the ventilation system in real time. RE is defined relative to baseline constant-ventilation operation according to the following equations (in all work done in this study, the baseline case is constant ventilation as prescribed in ASHRAE Standard 62.2 (ANSI/ASHRAE 2016):

$$\boldsymbol{R_i = \frac{Q_{tot}}{Q_i} + \left(R_{i-1} - \frac{Q_{tot}}{Q_i}\right) e^{-Q_{tot}\Delta t/V_{space}}} \qquad (1)$$

R_i = relative exposure for time-step, i
R_{i-1} = relative exposure for previous time-step, i-1
Q_{tot} = Target whole dwelling ventilation rate from ASHRAE 62.2-2016, m^3/s
Q_i = Ventilation rate from the current time-step, m^3/s
Δt = Simulation time-step, seconds
V_{space} = Volume of the space, m^3

In cases where there is no real-time and scheduled ventilation, then Equation 2 is used.

$$\boldsymbol{R_i} = \boldsymbol{R_{i-1}} + \frac{\boldsymbol{Q_{tot}\Delta t}}{\boldsymbol{V_{space}}} \tag{2}$$

Maintaining "equivalence" then requires satisfying two constraints:

1. Annual mean RE during occupied hours must be equal to or less than one.
2. At no time should RE exceed 5, in order to provide for acute exposure concerns.

All of these assumptions are codified in ASHRAE Standard 62.2-2016 (ANSI/ASHRAE (2016)), Normative Appendix C, and thus all strategies proposed in this work are compliant with the standard. This includes a limit on RE of 5 to prevent contaminants from exceeding acute levels based on work by Sherman, Logue, & Singer (2011) and Sherman et al. (2012) that investigated the ratio of acute to chronic exposure limits and set the relative exposure limit on the lowest ratio for contaminants of concern in homes.

Past work has used related approaches to develop and assess smart ventilation controls in homes in a variety of climates. A controller named RIVEC (short for **R**esidential **I**ntegrated **Ven**tilation **C**ontroller) was developed and briefly field-tested in California that used auxiliary fan sensing and timer-based temperature controls (Iain S. Walker, Sherman, & Dickerhoff, 2012). Less, Walker, & Tang (2014) studied the effects of several temperature-based control strategies that used cut-off temperatures below which IAQ fans were turned off (fan airflow were increased during all other hours). Smart controls for humidity control in hot and warm-humid climates were developed for similar homes in Less, Walker, & Ticci (2016). Less & Walker (2017) examined the performance of occupancy and auxiliary fan smart controls in Zero Energy Ready homes across U.S. DOE climate regions. A field study of a simple temperature-based control (Lubliner et al. 2016) showed that energy savings could be realized in a high-performance home. Finally, work at the Florida Solar Energy Center (Martin, Fenaughty, & Parker, 2018) has developed a multi-parameter smart ventilation controller using outdoor temperature and moisture levels, paired with pre-calculated seasonal ventilation targets. They also reported on limited field-testing of an occupancy-based smart controller deployed in a Deep Energy Retrofit home in the Pacific Northwest.

More consumer building products are emerging on the market that provide some form of ventilation control based on measured temperature and humidity, but which do not track relative exposure to preserve IAQ, and are not compliant with codes and standards. Products are diverse, costing between $50 and $300. They include a variety of either indoor or outdoor (or both) temperature and/or humidity sensors, and many are limited to use with certain fan types, or are embedded within certain fan technologies. Some controllers have hot-humid climate control features, but lack cold climate features. This suggests that products are available and can be economically integrated with systems, sensors and varied control features; what they lack are optimized controls that maintain compliance with ventilation codes and standards.

3 Control Strategies

We developed five classes of outdoor temperature-based SV control strategies that require only on/off fan control. For convenience we named these Lockout, Cutoff, Seasonal, MedRE, and VarRE, which are arranged in order of increasing complexity. We also looked at one strategy requiring a continuously variable fan drive (VarQ). Depictions of typical time series of relevant variables under each strategy are given in Figure 1, and strategies are described in detail below. All control strategies use IAQ fans that are over-sized relative to a constantly operating fan. This allows ventilation flows to be time-shifted, while still maintaining annual equivalence with the ASHRAE standard. Unless otherwise noted, all smart control fan airflows were double the matching baseline constant fan airflows. The control strategies studied here are focused on sensible load reduction in homes and were investigated in California climates that are not very humid. In more humid climates, one would need to also consider outdoor humidity, and smart ventilation controllers for humid climates have been developed elsewhere (Less and Walker (2016) and Martin et al. (2018)). In addition, other smart ventilation approaches are being developed to account for outdoor contaminants, such as periodic high particle or ozone concentrations. In this study these factors were not considered and all outdoor air is considered suitable for dilution of indoor-generated contaminants. Similarly, this study did not account for passive ventilation through stacks or open windows. Passive stacks are not used in typical US construction and window opening in the US is generally restricted to times when climate is mild and energy impacts are low (Price and Sherman

(2006)). Furthermore, this work is based on minimum acceptable air flow rates for dilution of indoor contaminants (ASHRAE 62.2-2016 is used as the basis for this) and window opening would only serve to increase ventilation above this minimum.

3.1 Timer Based Lock-Out (Lockout)

A lockout strategy is a simple timer-based strategy that controls ventilation based on the relatively predictable diurnal variation in outside dry bulb temperature rather than directly measuring outdoor temperature. Based on analysis of weather data files for California climate regions, we identified the six typically hottest and coldest hours for any given day: 2-7 a.m. in heating season and noon to 5 p.m. in cooling season. The smart controller turns the ventilation fan off during these hottest or coldest hours of the day (depending on season, as defined by the California Energy Commission in Title 24, Part 6[1]). We refer to this as the lockout period. During all other hours, the IAQ fan airflow is constant, and has been sized to ensure that the daily mean relative exposure will be less than or equal to 1.0.

3.2 Running Median (MedRe)

The "Running Median" strategy is the first to use measured temperature in the control strategy. This strategy targets custom high and low relative exposure values by comparing the current outside temperature (T_i) to its running median value ($T_{rollmedian}$). When in heating season, if T_i is colder than the running median, the ventilation is reduced (target RE_{high}), otherwise it is increased (target RE_{low}). Vice versa in the cooling season. RE_{high} and RE_{low} are selected to be equidistant from 1.0 (e.g., 1.3 and 0.7, or 1.5 and 0.5), so that when each value is maintained for 50% of the time, the resulting mean exposure is approximately 1.0. The high airflow target (RE_{low}) is initially designed to be the ratio of the baseline constant fan airflow divided by the over-sized smart fan airflow, which in this work led to values generally around 0.5. The corresponding low airflow (RE_{high}) values were then 1.5. The running median period was 30-days, so a mean RE of 1.0 was maintained during each month of the year. This control shifted ventilation airflows within days or weeks of the month, but not between months of the year or seasons.

3.3 Seasonal

The "Seasonal" strategy targets higher average exposure during heating season (reduced ventilation rate) and lower exposure during cooling season (higher ventilation rates), while maintaining a mean annual relative exposure of 1.0. Based on our past work (Less, Walker and Tang 2016), reducing the ventilation rate during the heating season (and increasing it during cooling season) has a net-energy benefit. Again using the Title 24, Part 6 definition of heating and cooling seasons, we first calculate the fraction of annual hours in each season for each climate region. A high exposure target (e.g., 1.4) is associated with the heating season, and the necessary low exposure target (e.g., 0.675) is then determined using a weighted average calculation based on the fraction of the year in the cooling season. As the high exposure target increases, the low exposure target must decrease. The low target is constrained by the fraction of annual hours in the cooling season, and by the smart fan over-sizing (i.e., if the smart fan airflow is double the reference flow, then a low RE target cannot be less than 0.5). We generally selected the highest exposure target for the heating season, where the corresponding low exposure target for the cooling season was achievable (i.e., >0.5). This procedure should provide an annual average RE very close to one, while maximizing the seasonal shift of ventilation airflows.

3.4 Optimized Cut-off Temperature Control (CufOff)

The CutOff temperature control strategy has two sets of RE targets, with the target RE chosen based on the outdoor temperature crossing a temperature threshold for each season. When temperatures are within the threshold the controller uses the seasonal RE targets from the Seasonal controller. When temperatures are more extreme, and beyond the threshold a different RE is targeted. For example, in the winter, when outdoor temperatures are relatively high (above the threshold temperature), the lowest relative exposure is targeted (target RE_{low}) and fan airflow is increased. When outdoor temperature is low (below the threshold temperature), the highest feasible RE is targeted (target RE_{high}) and fan airflow is decreased as shown in Figure 1. The seasonal threshold temperatures are selected for each case using an optimization routine, which identifies the combination of threshold temperature and high RE target that minimize estimated ventilation loads. The low RE targets were determined by the ratio of the reference fan airflow divided by the over-sized smart fan flow (generally 0.5), and were not subject to the optimization. A typical result was that the heating season mean RE target was 1.4, and within that season, a high RE target of 1.6 was controlled to

[1] The Title 24, Part California Energy Code uses a 7-day running mean of the outdoor dry-bulb temperature to determine the season. Heating season exists for any 7-day mean temperatures below 60°F (15.6°C), and cooling is for any period where the 7-day mean temperature is greater than 60°F (15.6°C).

during cold weather, and a low RE target of 0.5 was controlled to during mild periods. This approach avoids extended periods where the fan is completely off and limits peak exposures, which never exceed the RE_{high} value.

3.5 Optimized Variable Relative Exposure (VarRe)

Varying ventilation flows as a continuous function of outdoor temperature should allow for better optimization of the IAQ/energy balance. The “VarRe” strategy varies the RE target at each time-step proportionally to the difference between the coincident outdoor temperature and the thermostat setting, as illustrated Figure 1. The exposure values are inversely proportional to the outside temperature, with peak exposure and minimized airflow occurring at the most extreme hourly temperatures for each season (i.e., the coldest hour in winter and the hottest hour in summer). Airflow is maximized at all outdoor temperatures warmer than the thermostat setting in winter and cooler than the thermostat setting in summer. RE targets at each time-step are scaled linearly between a low and high RE target. The low RE target is once again fixed by the ratio of the baseline and smart IAQ fan flows, typically at 0.5. The high RE target is selected for each case and season using an optimization routine that identifies the highest pair of values (for heating and cooling seasons) that still maintain annual mean exposure below 1.0, while minimizing the estimated ventilation loads.

3.6 Optimized Variable Airflow (VarQ)

Similar to the VarRe control, the variable airflow controller scales IAQ fan flows to the difference between the coincident outdoor temperature and the thermostat setting, but it assumes use of a variable speed fan rather than just turning a fan on of off. This control scales the target fan airflow between off and maximum in response to outdoor temperature signals. In the VarRe controller, the scaling used the annual coldest and hottest temperatures, and then optimized the high RE target. The VarQ control has fixed high and low airflows, and an optimization process is used to select different extreme temperatures to be used in the scaling. For example, if the annual minimum temperature was -5°C, the optimization may instead have selected to scale airflows only down to 6°C, effectively turning the IAQ fan off for all hours <6°C. For each house and climate region, we identified the optimal extreme temperatures to use in scaling fan airflows, which minimized estimated ventilation loads. We illustrate an example strategy across a range of outside temperatures in Figure 1. The heating season airflow (blue line) is set to zero when outside temperature is below the T_{max} value (roughly 7°C here), it scales fan airflow linearly up to the maximum airflow, when outside air is the same as the thermostat setting (18°C), and the fan airflow remains at maximum at all temperatures that are warmer than the thermostat setting (free heating). The opposite happens in cooling season.

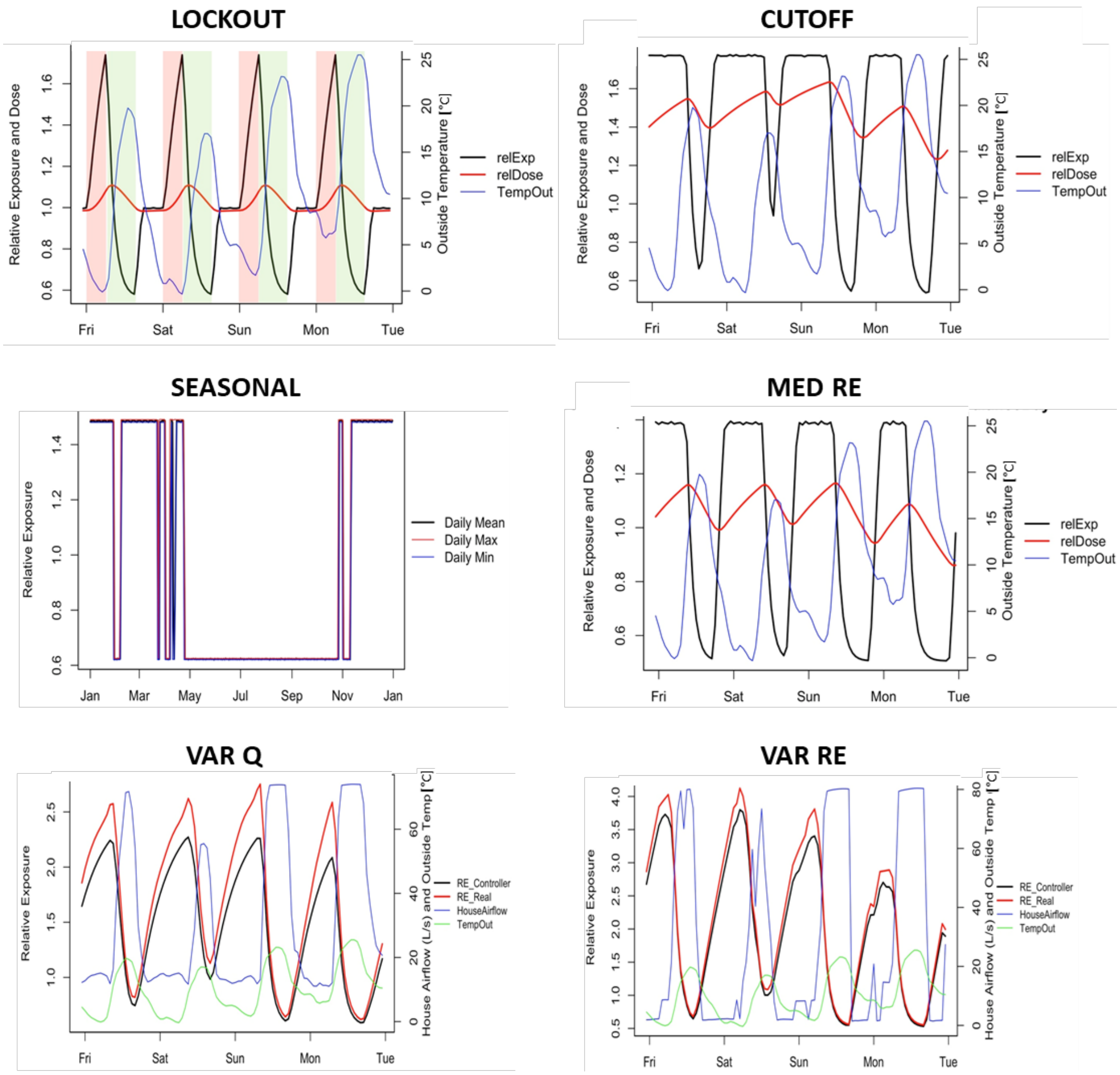

Figure 1. Typical time series of variables of interest under each of the six classes of control strategies studied

4 Modeling and Analysis Methodology

In order to study the energy and IAQ benefits and consequences of SV strategies, we first created a combined energy-IAQ model of two representative California home types, in several different California climates. We then analyzed the performance of these homes with respect to both energy and IAQ under a variety of different SV control strategies.

4.1 Homes simulated

We simulated homes matching the specifications of the two CEC single-family prototype units (Nittler & Wilcox, 2006), whose properties are made to align as well as possible with the prescriptive performance requirements (Option B) in the 2016 California Building Energy Efficiency Standards (commonly referred to as "Title 24", terminology we will use henceforth in this paper). We created detailed models of two prototype homes: a 1-story 2,100 ft^2 (195 m^2) prototype home and a 2-story 2,700 ft^2 (251 m^2) prototype home, with forced air space conditioning systems. The HVAC was sized using Air Conditioning Contractors of America Association Manual J (ANSI/ACCA 2016) load calculation procedures, with thermostat schedules set to meet those specified in the Title 24 Alternative Calculation Manual (California Energy Commission 2016c).

A key part of this study was to investigate the effects of ventilation controls on more advanced energy efficient homes, so several deliberate deviations were made from the code-minimum Title 24 prescriptive path prototypes; we did not include whole house economizer fans that are part of the prescriptive packages for homes in climate zones 8-14; we improved the HVAC equipment efficiencies beyond prescriptive minimums to SEER 16 A/C and 92 AFUE gas furnaces in order to align with standard new construction practice; and we did not model any duct leakage, in order to reflect the advanced building strategy of placing HVAC ducts inside conditioned space.

Visual representations of the two homes are given in Figure 2, a list of home simulation input parameters is given in Table 1, and HVAC input parameters are given in Table 2. Input files are available upon request via email.

Figure 2. Rendering of two prototype homes simulated: a 1-story 2,100 ft^2 (195 m^2, top) and a 2-story 2,700 ft^2 (251 m^2, bottom)

Table 1. Model input values for prototype homes

Element	*Prototype 1*	*Prototype 2*
Ceiling height (ft)	9	9
Conditioned Floor Area (ft2)	2,100	2,700
Conditioned Volume (ft3)	18,900	25,750
Gross Areas		
Slab (ft2)	2,100	1,250
Slab perimeter, outside (ft2)	162	128
Slab perimeter, garage (ft2)	30	30
Ceiling (ft2)	2,100, unvented attic	1,450, unvented attic
Roof slope (%)	20	20
Roof Deck R-value	R13 (airspace) below deck insulation, in CZ4 and 8-16	R13 (airspace) below deck insulation, in CZ4 and 8-16
Ceiling Insulation	R38 (R30 in CZ3, 5, 6 and 7)	R38 (R30 in CZ3, 5, 6 and 7)
Radiant Barrier	No	No
Wall U-value	0.051 (0.065 in CZ6&7)	0.051 (0.065 in CZ6&7)
Slab Perimeter R-value	0 (7 in CZ16)	0 (7 in CZ16)
Window U-value	0.32	0.32
Window SHGC	0.25	0.25
Window Area	20% floor area	20% floor area
Gas Furnace AFUE	92%	92%
AC SEER	16	16

Table 2. HVAC system variables for each climate region.

CZ	***Air Handler Fan Efficacy {W/cfm}***	***Air Handler Flow Rate (cfm)***	***Rated Total Cooling Capacity (W)***	***Rated Cooling COP (W/W)***	***Gas Heater Nominal Capacity {W}***	***Gas Burner Efficiency AFUE***
1	0.365	593	5275	3.95	7033	0.92
3	0.365	593	5275	3.95	7033	0.92
10	0.402	996	8792	3.95	7033	0.92
16	0.365	805	7034	3.95	7033	0.92

4.2 Climates

Locations were selected that represented a broad range of climatic conditions in California. It was important to capture the variety of heating, cooling and moisture regimes throughout the state, in order to allow statewide estimates based on weighted average calculations.

Table gives the climatic design data for 4 representative cities, from the harshest Blue Canyon (CZ16) to the very temperate Oakland (CZ3), and Riverside (CZ10) that represents a location with greatest growth in new construction and higher cooling demand.

Table 3. Climate zone design information, including heating and cooling degree days calculated at 18.3°C reference temperatures, and heating/cooling design temperatures.

CEC Climate Zone	$HDD_{18.3}$	$CDD_{18.3}$	Design Temperature (Heating – Cooling, °C)
1 – Arcata	2,658	1	0.6 / 20.6
3 – Oakland	1,436	85	2.2 / 26.7
10 – Riverside	1,011	888	1.7 / 37.2
16 – Blue Canyon	3,174	151	-4.4 / 27.2

We used the data (dry-bulb temperature, dew-point temperature, wet-bulb temperature, wind direction, wind speed, global horizontal irradiance, direct normal irradiance, diffuse horizontal irradiance and total sky cover) from the CEC compliance weather files, to generate corresponding .epw files to be used in EnergyPlus. Where required, we converted these values from the IP system in the CEC .epw files to SI units for use in EnergyPlus. Relative humidity was derived using dry-bulb and wet-bulb temperatures from the CEC file with the paired atmospheric pressure from EnergyPlus weather files for the same locations.

4.3 Development of Building Model

To model the energy and IAQ implications of our various control strategies we used a co-simulation based approach, using CONTAM to perform mass and contaminant balances, and EnergyPlus to model energy consumption and implement smart ventilation controls and calculations. Our method was based on an approach developed and validated by the National Institute of Standards and Technology (Dols, Emmerich, & Polidoro, 2016), with a number of significant differences discussed later in this paper. Dols et al. used a Functional Mockup Unit- (FMI, http://fmi-standard.org/) based implementation of CONTAM, which is then coupled to EnergyPlus via its FMI implementation (Thierry Nouidui, 2014) .

We used EnergyPlus to model the building envelope, HVAC system and controls, occupants and building energy use. EnergyPlus input files for the two prototype homes were first generated with BEopt. BEopt implements residential-specific models in EnergyPlus using a simple graphical user interface, including user-friendly specification of building geometry and performance features, along with residential defaults for internal heat gains, appliance and lighting usage, etc.

We used CONTAM to model the air flow mass balance including inter-zonal air flow between the attic and living space, mechanical air flows and natural infiltration, and contaminant transport. The geometry, aspect ratio floor area and zone heights were also specified to match the EnergyPlus model. In total, we developed six different CONTAM files: three levels of air tightness for each of the two prototype home sizes; there is no variability in CONTAM models by climate zone. Each model effectively had two well-mixed thermal zones to match the corresponding EnergyPlus model: The main conditioned living area which we were analyzing, and the attic, which was used to appropriately treat the ceiling airflows and any HVAC system interactions with the attic.

The IAQ fan controls are incorporated into EnergyPlus via user-defined Energy Management System code and the energy consumption is accounted for in EnergyPlus via scheduling of the IAQ fan object model in EnergyPlus. The mass flows associated with IAQ and auxiliary fans are transferred to CONTAM. These mass flows are represented in CONTAM as “flow paths”. CONTAM then calculates the resultant infiltration and inter-zonal mass flows, considering these mechanical flows, along with wind driven and stack effects to determine the resultant mass flow rate. This infiltration is then returned to EnergyPlus to align the two models’ air change rates and mass balances.

After the baseline models were developed, we performed a series of verification exercises to ensure that the predicted results from these models substantively agreed with previously validated models, and any observed differences were rationalized. We previously extensively validated an in-house simulation platform with regards to air exchange rates and interaction of ventilation system with envelope air exchange. This validation is detailed in Walker, Forest and Wilson (2005). For the purposes of this work, we simply applied the same driving conditions (indoor-outdoor temperature difference and façade wind pressures) for ten different representative conditions and verified that the same air exchange rates were calculated by each simulation platform. As BEopt, EnergyPlus and CONTAM have been extensively validated over the past few decades and the ventilation was the only system modified in the course of this work, we considered this sufficient validation.

Once we were satisfied with the dynamics reflected in the EnergyPlus models from BEopt, these were then modified to include the objects that handle the interactions with CONTAM via the FMI, and our EMS control code. These EMS programs influence the behavior of the model, principally by setting values of commonly used EnergyPlus objects (schedules, infiltration flows, etc.), using an EnergyPlus object called an *Actuator*. At each timestep, environmental data (wind speed, direction and outdoor temperature), and system operation data (mechanical system flows), are sent from EnergyPlus to CONTAM. The EnergyPlus Energy Management System (EMS) is used to manage this interchange and to implement required calculations and control strategies.

4.4 Normalization and Energy Savings Estimates

In the raw simulation results, the annual mean relative exposure is not always equal to one, either in the baseline continuous fan or smart control cases. Values were typically clustered in the range from 0.95 to 1.05, though more extreme values also occurred. This means that the energy comparisons would also include changes in IAQ. Because it is trivial to save energy by worsening IAQ (or to use more energy by improving IAQ), we need to compare results at the exact same exposure. To do this, we normalized the site energy by the annual mean controller exposure for each case.

To isolate the energy use attributable to the ventilation and natural infiltration air flows separate from the other building envelope heat losses and gains we performed a set of simulations that had no air exchange either through fans or natural infiltration. This envelope energy use was subtracted from the HVAC energy use to estimate the total energy consumption added to the home by outside air exchange. This ventilation energy was then multiplied by the annual mean controller exposure for each case, in order to estimate the ventilation energy use that would have occurred if the controller exposure was exactly 1.0. For example, if a case was slightly over-ventilated relative to the target airflow (e.g., mean exposure of 0.98), the ventilation energy use in that case was multiplied by 0.98 to approximate the slightly lower ventilation energy use that would have occurred if exposure were equal to 1.0. This normalized ventilation energy was then added back onto the envelope-only energy use for each case, and these adjusted HVAC energy use values were used to estimate energy savings of smart controls relative to baseline continuous IAQ fan cases.

For each smart control case, there were two corresponding baseline cases. One with no IAQ fan and another with a constant flow IAQ fan sized to comply with ASHRAE 62.2-2016. Each of these baseline cases included natural infiltration airflows and auxiliary exhaust fan flows (e.g., from exhaust fans in bathrooms, kitchens and laundry areas). The total HVAC energy associated with complying with the ASHRAE 62.2-2016 standard using a constant flow IAQ fan is the difference between these two baseline cases. This is referred to as the “ventilation energy”, and it includes all heating and cooling energy use associated with conditioning the outside air introduced by the IAQ fan, as well as the fan energy use itself. For each smart control case, we calculated the energy savings as the difference between the matching smart case and the constant fan baseline case. We report these savings in terms of raw kilowatt-hours (kWh), as well as in relative percent terms, by dividing the smart control savings by the ventilation energy associated with compliance with ASHARE 62.2-2016 using a constant fan.

5 Results

The following sections describe the energy savings results generated in the simulation program. We first present an overview of energy savings distributions and weighted averages, and then break down the results into end-use, time-of-use savings, and control strategy.

5.1 Energy Savings Summary

The results are summarized in Table 4. The fractional energy savings were determined by averaging the energy savings and dividing by total energy used in the baseline simulations. The best performing controls save over 30% while increasing the whole house ventilation airflows by roughly 30%. The peak relative exposure was increased above 1.0 for all control types, reflecting periods of reduced ventilation airflow but was never greater than 2.9 and not close to the limit of 5 set for possible acute exposures. The best controls all shifted ventilation airflows seasonally, with increased flows during summer and reduced flows during winter. In addition, within each season, the VarRe and VarQ controls also modulated airflows in response to mild or severe conditions. Without this modulation within each season, savings were reduced, as reflected in the weighted average savings for the Season controller. These results suggest that modulation of flows within the season gains another 10% ventilation energy savings on top of season-based control. Conversely, the controls that shifted ventilation only within a day (LockOut) or within a month (MedRe) had much lower savings estimates, with the Lockout control marginally increasing energy use. This is mainly due to cases of insufficient temperature difference between the on and off periods.

Table 4. Summary results for SVC, including relative exposure, air exchange rates, and site energy savings.

Control Strategy	% AER Increase	Peak Occupied Exposure	Site Energy	
			Ventilation (%)	Total (kWh/year)
CutOff	21	1.4	25	530
Lockout	16	2.0	-2	-42
MedRe	16	1.2	5	99
Season	22	1.3	22	474
VarQ	22	2.9	31	646
VarRe	23	2.1	33	698

Figure 3 shows the variation in ventilation energy savings – this time all the data are presented and the median values represent the median fractional savings for the % savings plot. The typical fractional savings are higher than the results in Table 4. The box plots show the median and the spread of results (due to changes in climate, envelope leakage, air tightness, etc.). The cases where energy use increased for the LockOut, MedRe and CutOff control strategies ere all in CZ1. These distributions show that the highest energy savings are generally from the controllers with the greatest variability in performance. the CutOff, VarRe and VarQ controllers have by far the highest average ventilation savings. The worst performing controls were the LockOut and MedRe, while the Seasonal controller falls between these two categories. The top performing controls saved just shy of 40% ventilation energy on average, with absolute energy reductions in the range of 500-600 kWh per year. All control strategies had widely varying energy savings estimates, often covering nearly the entire range from 0 to 100% savings.

For all of our control types, CZ1 was very difficult to achieve meaningful ventilation energy savings. This is because it does not have the large diurnal temperature swings that occur in many other locations in California that allow ventilation shifting through hours of the day or large temperature changes between seasons.

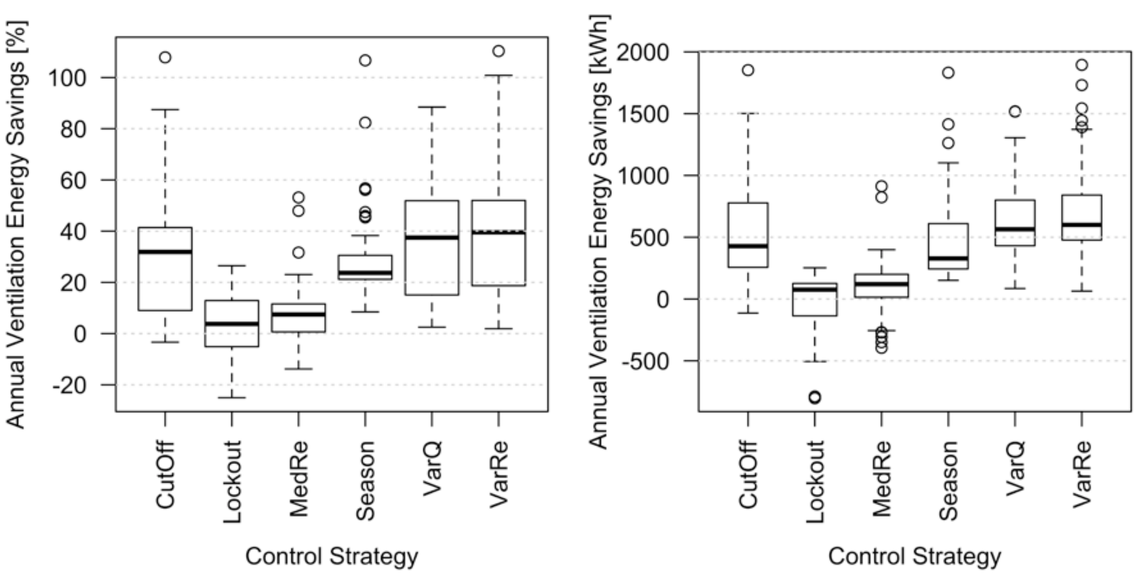

Figure 3. Ventilation energy savings (relative % and absolute kWh) for each smart control type.

5.2 Weighted Average Performance

Because the results of this work are being used to advise policy decisions regarding state-wide building codes, we combined the results for individual climates weighted by the proportion of statewide new construction in each climate and the proportion of single vs. two-story single-family homes in new construction and the fraction of homes at various airtightness levels (described in Appendix A). This approach gives strong weight to the 3 and 5 ACH_{50} cases in climate zones 3 and 10 (93% and 96% of total weight for new construction by airtightness and climate zone, respectively).

Table 5 presents the weighted average results for each strategy, including the maximum (peak) relative exposure experienced, the increase in annual ventilation rate (AER) and absolute and relative ventilation energy savings.

This weighting increased the site energy savings with the best performing controls (CutOff, VarRe and VarQ) having savings ranging from 48-55%, while increasing the whole house ventilation airflows by roughly 30%. This represents total HVAC site savings between 13 and 15%. The best controls that modulated airflows in response to mild or severe conditions gained another 20-25% ventilation energy savings on top of season-based control. The controls that shifted ventilation only within a day (LockOut) or within a month (MedRe) still had the lowest savings estimates of 11 and 15% ventilation energy. These increases in savings are because new construction in California is focused in climates that have the larger diurnal and seasonal temperature changes.

Table 5. Weighted average summary results for SVC, including relative exposure, air exchange rates, and site energy savings.

Control Strategy	**% AER Increase**	**Peak Occupied Exposure**	**Site Energy**	
			Ventilation (%)	Total (kWh/year)
CutOff	31	1.7	48	561
Lockout	17	1.9	11	133
MedRe	13	1.2	15	176
Season	25	1.4	29	340
VarQ	28	2.4	54	634
VarRe	29	2.3	55	651

5.3 Savings by End-Use

Site energy end-use savings are aggregated by control type, and median values are shown in Figure 4. Energy saving are dominated by heating energy for all controls, with over 90% of total savings falling into the heating category. Due to the increased mechanical fan airflows, IAQ fan energy use (purple bars) increased marginally in all smart control cases, but this was more than offset by the thermal benefits of time-shifting the ventilation. Cooling energy use increased for the Seasonal control, which simply reduced airflows in the winter and increased them in the summer. This had predictable negative consequences on cooling energy use, and though they maintained this same average seasonal shifting, the more advanced controls managed to save cooling energy by curtailing ventilation during hot periods.

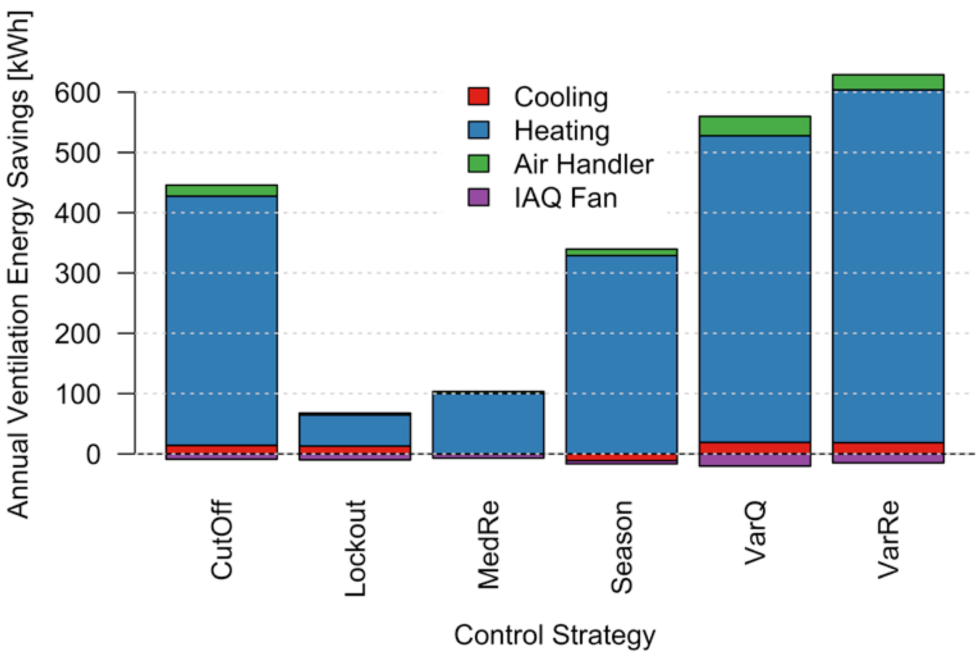

Figure 4. Median ventilation energy savings by end-use category. Aggregated by control type.

5.4 Maximum Savings for Each Scenario

In Figures 5 and 6, for each simulated home (i.e., combination of climate zone, prototype and airtightness), we show the control type with the highest energy savings. The VarQ (pink) and VarRe (grey) controllers are most commonly the best performing for any given home, with one individual case maximizing savings with the MedRe in CZ1. With the exception of CZ1, most cases were able to achieve site ventilation energy savings between 20 and 70% (500 to 1,500 kWh/year). Notably, while the percent ventilation energy savings in CZ1 were much lower than in other climate regions, the absolute savings are similar to those in CZ3, they just represent smaller fractions of the total ventilation energy consumption, because the thermal loads are so much greater in CZ1. Climate zone 10 (Riverside) is representative in our analysis of a climate that dominates new home construction in California, and in these locations, we estimate energy savings between 40 and 70% across house prototypes and airtightness levels.

For any given house (prototype plus climate zone), fractional savings increased with envelope leakage. This effect was greatest in CZ16 and least in CZ1 and CZ10. This is because of the interactions between natural infiltration (that vary with airtightness) and mechanical ventilation. This result is interesting as it implies that SV controls could offset a considerable amount of the energy penalty of less-tight envelopes and might be a more cost-effective strategy for ventilation-related energy savings in either new construction specifications or when retrofitting existing homes. Prototype effects were mixed, in that sometimes the 1-story homes outperformed the 2-story homes (in CZ 3 and 10). While in CZ1 and 10, the 2-story cases had higher percent savings. With the exception of CZ1, percent ventilation energy savings were fairly consistent across the remaining climate regions, with individual exceptions, such as the 2-story 5 ACH_{50} home in CZ16.

Absolute energy savings generally have increasing maximum savings values going from CZ1 to 3 and 10. In CZ16—the cold, mountainous region of California—absolute savings increase dramatically; increasing with both envelope leakage number of stories. Aside from in CZ16, there are no evident trends in maximum absolute savings with either airtightness or prototype/number of stories.

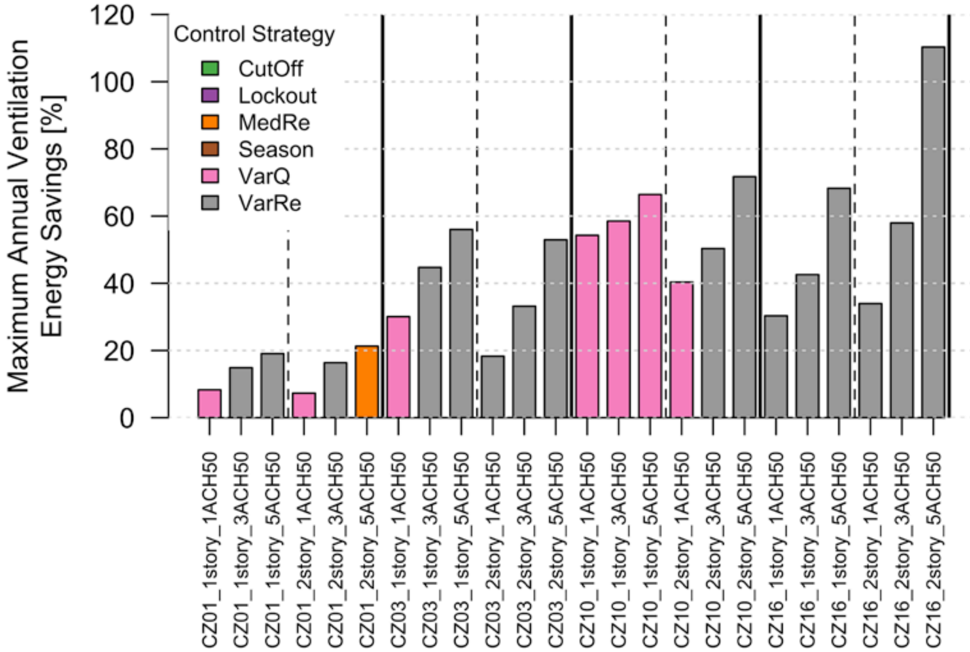

Figure 5. Site energy relative savings. Maximum for each case.

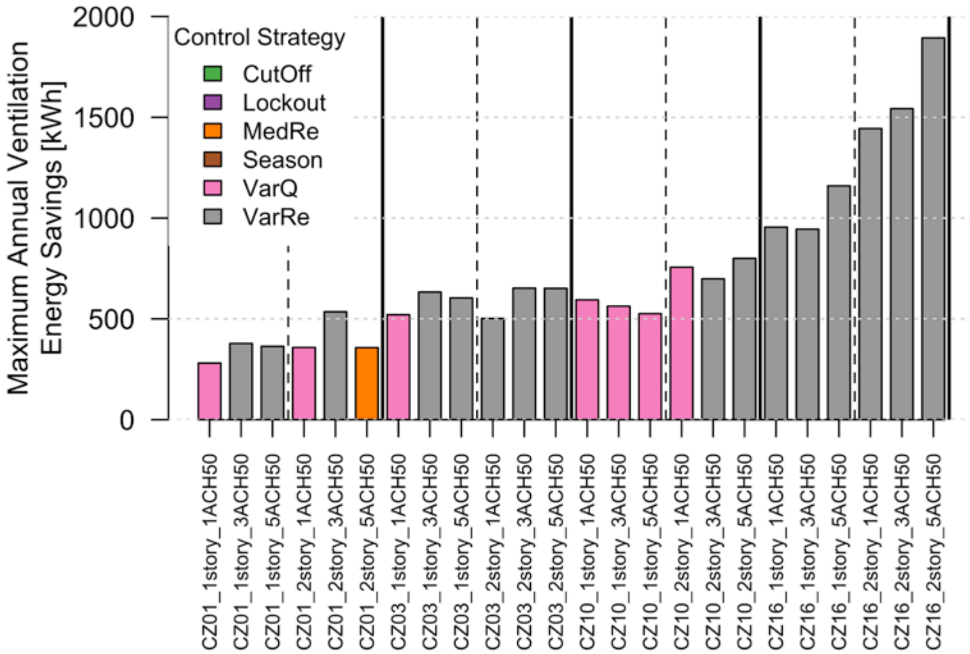

Figure 6. Site energy absolute kWh savings. Maximum for each case.

6 Conclusion and Limitations

Temperature-based smart ventilation controller performance varied substantially by climate zone, airtightness and house prototype. Several general conclusions can be drawn about the efficacy of the strategies studied herein:

- Controller performance variability is significant – particularly between different climates. However, the controls studies here gave energy savings in almost all situations. This is in contrast to previous work on occupancy-based ventilation control in similar homes which found minimal savings in many cases (Clark et al. 2019).
- The most successful smart controls reduced weighted average site ventilation energy use by about one-third (roughly 650-700 kWh/year or 10-13% of whole house HVAC energy use) with some controls in specific climates at least doubling the fracitonal savings.
- The vast majority of site energy savings were for heating end-uses (>90% of total savings).
- On average, whole house ventilation rates increased 30% for the best controls, and anywhere from 0 to 40% for individual cases. Typical increases were in the range of 10-30%.
- Smart controls were generally ineffective in climates that have low diurnal or seasonal temperature variation (e.g., CZ1 Arcata in California).
- Controls that shifted ventilation rates seasonally, rather than over the course of the day or month, were the most effective. These controls maintained lower overall ventilation rates during the heating season and increased ventilation rates during the cooling season, though the best controls also reduced ventilation during cold hours and increased ventilation during mild periods in the heating season. This modulation within each season boosted savings by an additional 10% over a simple seasonal controller.
- Controls that were designed using an optimization strategy to select parameter values that minimized estimated ventilation loads were the most effective.

Limitations

Several limitations on the applicability and validity of this work exist.

First, this study was limited to investigations in the State of California. We were also limited in the number of home types we simulated. Similar investigations used to quantify efficacy of energy efficiency measures for the purpose of code development have analyzed the same two prototype homes- a 2,100 ft^2 single story prototype and a 2,700 ft^2 two-story prototype (Hunt et al. 2016). We chose to continue this convention in order to provide guidance on things such as how much credit might be taken in prescriptive codes for smart ventilation strategies, and ensure our conclusions were made on the same basis as previous studies of the same type. Performance of other homes will vary.

With regards to the climates analyzed, we chose four climates that spanned the range of conditions found in the state of California and also captured the areas with the greatest amount of new residential construction. We chose these four climates to allow for qualitative interpolation between them.

We included inputs to the simulation campaign that have effectively been standardized for this type of analysis but do not reflect the diversity of ways that a building might operate. For example, occupancy patterns that deviate significantly from those modeled may affect conclusions of this work significantly. Similarly, homes with different systems, homes in which windows are opened often, and those with geometries and sizes deviating significantly from the homes modeled will likely produce different savings with the strategies modeled.

Acknowledgments:
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8 Appendix A. Weighted Average Method

In addition to reporting results across the house and simulation parameters described above, we also perform a weighted average assessment, which is targeted towards representing SV control performance in new homes built in California. As such, the weighted average method gives strong emphasis to the types of homes that are built in the state and where they are built. Namely, this means strong weighting for cases with more air leakage in climates 3 and 10 (Oakland and Riverside).

Each case is weighted according to the expected distribution of the parameter in new homes throughout the state. The weighted average parameters used in our analysis included climate zone (see Table A3 and A4), envelope airtightness (Table A1) and house prototype (Table A2). Each factor is briefly discussed below. This is an imperfect approach to characterizing the entire new California single-family building stock, but it does give us a way to generalize and summarize our results. For example, this method gives greater weight to results from the mild climate zones in Southern and Central California where most new home development occurs in the state, and it reduces the effect in sparsely populated zones, like CZ1 (Arcata) or 16 (Blue Canyon). The average result under these weights for each fan sizing method was calculated using Equation A1.

$$\overline{\boldsymbol{x}} = \frac{\sum_{i=1}^{n}(x_i * w_{prototype,i} * w_{cz,i} * w_{ACH50,i})}{\sum_{i=1}^{n} w_{prototype,i} * w_{cz,i} * w_{ACH50,i}} \quad \textbf{(1)}$$

x = Variable in question (e.g., relative exposure, ventilation energy use)
$w_{prototype}$ = house prototype weight
w_{cz} = climate zone weight
w_{ACH50} = airtightness weight
The airtightness weights (A1) are designed to roughly estimate current airtightness in new California homes, with most new construction achieving roughly 5 ACH_{50}, and diminishing numbers of new homes achieving 3 ACH_{50} and very low numbers with greater airtightness of 1 ACH_{50}.

	Envelope Airtightness (ACH_{50})		
	5	3	1
Estimated Weights	0.63	0.30	0.07

Table 1 Envelope airtightness weighting factors

Prototype weights (A2) match those provided in the description of the single-family Title 24 prototype buildings that are used for analysis supporting development of the Title 24 energy code (Nittler & Wilcox, 2006).

	1-story, 2,100 ft^2	2-story, 2,700 ft^2
Weighting Factor	0.45	0.55

Table A2 Prototype weighting factors

Climate zone weights (Table and A4) are based on the fraction of total projected new housing starts in 2017 in each CEC climate zone, using data provided to the 2016 CASE teams by the CEC Demand Analysis office. We have reproduced exactly the estimates provided by Rasin & Farahmand (2015) in Table 14 of the Residential High Performance Walls CASE report. Yet, we simulated only climate zones 1, 3, 10 and 16, and we attribute projected housing starts in non-simulated climate zones based on geography and overall heating/cooling degree days (see Table for our assignment of non-simulated climates to those we simulated, for example, the CZ4 and CZ5 weights were added to the CZ3 weighting). The combined weights for zones 1, 3, 10 and 16 are provided in Table A3. The vast majority of weight (96%) is applied to the CZ3 and 10 results.

CZ	City	2017 New Single-Family Homes	2017 New Homes Fraction	Rough HDD_{65} Range	Rough CDD_{80} Range	CZ Weight Assignment
1	Arcata	695	0.006	3800-4500	0-50	1
2	Santa Rosa	2602	0.024	2600-4200	200-900	3
3	Oakland	5217	0.048	2500-3800	10-500	3
4	San Jose-Reid	5992	0.055	2300-2900	200-1000	3
5	Santa Maria	1164	0.011	2300-3000	200-900	3
6	Torrance	4142	0.038	700-1900	500-1200	10
7	San Diego-Lindbergh	6527	0.060	1300-2000	500-1100	10
8	Fullerton	7110	0.066	1300-1800	700-1300	10
9	Burbank-Glendale	8259	0.076	1100-1700	1300-1600	10
10	Riverside	16620	0.154	1600-1900	1400-1900	10
11	Red Bluff	5970	0.055	2500-4300	600-1900	3
12	Sacramento	19465	0.180	2400-2800	900-1600	10
13	Fresno	13912	0.129	2000-2700	1000-2200	10
14	Palmdale	3338	0.031	1900-2700	2000-4200	10
15	Palm Spring-Intl	3885	0.036	1000-1300	4000-6600	10
16	Blue Canyon	3135	0.029	4300-6000	200-1000	16

Table A3 New construction estimates for single-family homes in 2017 and weighting assignments for un- simulated climate zones.

	1 (Arcata)	3 (Oakland)	10 (Riverside)	16 (Blue Canyon)
Total Weight Factor	0.0064	0.1939	0.7707	0.0290

Table A4 Climate zone weighting factors.